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Effect of the planetesimal disk on the positions of the secular resonances in the primordial Kuiper Belt

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Abstract

During the pre-instability period following the disappearance of the protoplanetary gas disk, the giant planets were in a compact multiresonant orbital configuration, before starting to migrate by interacting with a planetesimal disk extending beyond the orbit of Neptune. It is commonly accepted that the disk was divided into two parts: a massive disk extending from Neptune to 30 AU and a low mass extension of the disk extending beyond 30 AU. We study the effect of the massive part of the disk on the nodal precession of the giant planets and of the planetesimals in order to find the positions of the secular resonances. The presence of the massive disk removes the degeneracy of the f_5 nodal frequency and allows for a new secular resonance. We show that for some orbital configurations, the f_5 nodal secular resonance is located in the region where the primordial cold classical Kuiper Belt formed.

1. Introduction

In order to reproduce the difference between the dynamically hot and cold populations of the Kuiper Belt, current models of dynamical evolution aiming to reproduce the orbital structure of the Kuiper Belt consider that the two populations formed from two different regions. The hot population is assumed to be formed from a massive disk (within the range $\sim 10-60\,M_\oplus$) extending between Neptune and 30 AU and the cold population from a light disk extending beyond 30 AU. The sharp edge at 30 AU also allows Neptune to stop its planetesimal-driven migration at this semi-major axis. In numerical integrations reproducing the cold population [5], the massive disk is only considered through fictitious forces aiming to mimic the planetesimal-driven migration of the giant planets, because it would be computationally to heavy to include all the direct interactions. However, before the dynamical instability between the giant planets, which strongly depletes the mass of the planetesimal disk, the massive part of the disk can have a significant influence on the apsidal and nodal precessions of the giant planets and of the planetesimals, leading to the shift of the positions of the secular resonances. In particular, as it has already been noticed by Nagasawa and Ida for the protosolar nebula [4], the presence of a massive disk removes the degenaracy of the f_5 nodal frequency and allows for a new secular resonance. We investigate these effects in the linear secular theory of Lagrange-Laplace and find the locations of the secular resonances for different multiresonant orbital configurations of the giant planets. The apsidal precession is not investigated here because the resonant terms are more important than the secular terms in the apsidal part of the distrubing function and in this case a simple linear secular theory does not allow the analyse of the apsidal precession frequency.

2. Model

We consider the giant planets in their primordial multiresonant configuration and an axisymmetric thick disk with an inner edge at 1 AU from Neptune and an outer edge at 30 AU. We calculate the potential induced by the massive disk, using the method developed by Fukushima [3]. From the linear secular theory, and including the effect of the massive disk, we determine the nodal eigenfrequencies of the planetary system and the nodal precession frequency of a small body (massless body) as a function of its semi-major axis. Secular resonances occur where the free precession frequency of a small body equals one of the eigenfrequencies of the planetary system. We also performed a few numerical integrations in order to illustrate the effect of the f_5 secular resonance. The nodal precessions caused by the disk are included through fictitious forces.

3. Results

Table 1 shows the positions of the f_5 secular resonance in the different multiresonant configurations of the giant planets explored by Deienno et al. [2] during the pre-instability phase. We also tested different masses for the massive disk. We can see that, for some orbital configurations the f_5 nodal secular resonance is located in the region where the primordial cold classical Kuiper belt formed.

Table 1: Positions of the f_5 secular resonance for different multiresonant configurations of the giant planets and different masses of the massive disk.

Orbital configuration	M_{disk} ($M_\oplus$)	Position of f_5 (AU)
3:2, 3:2, 4:3, 4:3	20	42.74
	40	40.95
	60	40.54
3:2, 3:2, 3:2, 3:2	20	44.96
	40	43.53
	60	43.35
3:2, 3:2, 2:1, 3:2	20	48.26
	40	47.53
	60	47.67
3:2, 3:2, 2:1, 2:1	20	55.13
	40	54.69
	60	54.71

Figure 1 shows the results of three different numerical integrations after 10 Myr, in the classical belt. The giant planets are kept in the multiresonant configuration 3:2, 3:2, 2:1, 3:2. The mass of the massive disk is initially $M_{disk} = 20M_\oplus$ but it decreases exponentially with a timescale $\tau = 50$ Myr, allowing for the secular resonances to sweep. To illustrate that the efficiency of the f_5 secular resonance depends on the inclination i of the plane orthogonal to the total angular momentum of the giant planets (hereafter called the planetary plane) with respect to the mean plane of the disk, we did simulations with three different inclinations of the planetary plane: $i = 0°$, $i = 1°$ and $i = 2°$. The effect of the f_5 secular resonance is strongly visible near 49 AU. It shows that the nodal precession due to the massive disk can not be neglected although the exact position of the f_5 resonance depends on the orbital configurations of the giant planets and its efficiency depends on the inclination of the planetary plane with respect to the massive disk.

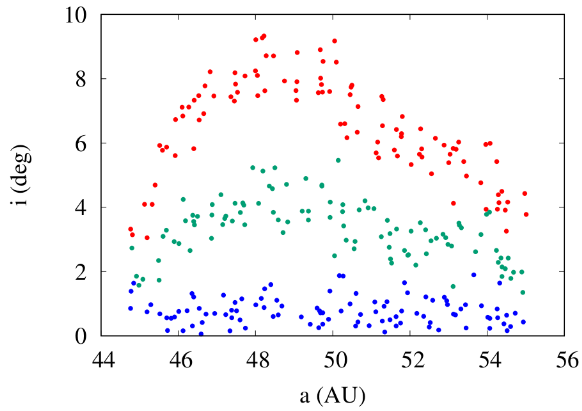

Figure 1: Inclinations of the particles in the classical belt after 10 Myr integrations. We consider three different initial inclinations i of the planetary plane with respect to the plane of the massive disk: $i = 0°$ (blue dots), $i = 1°$ (green dots) and $i = 2°$ (red dots).

References

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